AD-A191 478   A DYNAMIC ANALYSIS OF PIEZOELECTRIC STRAINED ELEMENTS   1/1
(U) TECHNICAL UNIV OF ISTANBUL (TURKEY) FACULTY OF
AERONAUTICS AND ASTRONAUTICS M C DOEKMECI OCT 87

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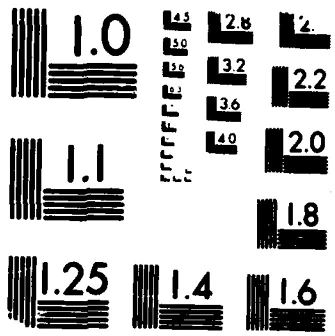

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A. (1) Title of Research Project:

A DYNAMIC ANALYSIS OF PIEZOELECTRIC STRAINED ELEMENTS

(2) Name of Principal Investigator:

M. Cengiz DÖKMECİ

(3) Name of the Contractor:

Istanbul Technical University

Faculty of Aeronautics and Astronautics

Office of the Dean

P.K.9, ISTANBUL 80191

TURKEY

(4) Contract Number:

DAJA45-86-C-0035

(5) 1st Periodic Report

December 1985-February 1986

(7) "The Research reported in this document has been made possible through the support and sponsorship of the U.S. Government through its European Research Office of the U.S. Army. This report is intended only for the internal management use of the Contractor and the U.S. Government."

2nd PERIODIC JULY 86
3rd PERIODIC MAR 87

B. (1) In the first part of study, the existing work pertaining to the dynamic applications of piezoelectric crystals is reviewed with emphasis on the effect of initial stress. More than three hundred works are surveyed in the current literature concerned with the dynamic applications. Then, an update review article with two hundred and thirty three representative articles, entitled: "Dynamic Applications of Piezoelectric Crystals", is submitted for publication in The Shock and Vibration Digest.

The review article deals with the current literature that pertains to recent applications for waves and vibrations in piezoelectric crystals. Accordingly, it supplements the earlier review papers [1-3] and should be considered in conjunction with them. The present compilation summarizes the rapid advancement of the subject due to the demand of both civil and military technology during the last three years.

The article contains five sections. The first section with thirty five references has to do with the theoretical and experimental fundamental studies. The nature of piezoelectric materials, the basic equations of piezoelectricity and the associated variational formulations are taken up, and especially, the studies concerning with strained piezoelectric continua are indicated. The second section with one hundred and six references reviews vibrations of piezoelectric structural elements, including those with initial stresses. The analytical and corroborated experimental studies are surveyed for the vibrational characteristics of structural elements which are mostly used in piezoelectric devices. Investigations are indicated for the analysis of piezoelectric rods, plates, discs, shells and composite elements. Due to their extensive use as a design feature in devices, studies concerning the dynamic behavior of piezoelectric circular and rectangular plates are continued to grow at a rapid pace after the publication of previous reviews

[1-3]. The third section with sixty four references is devoted to the survey of works on acoustic waves and energy trapping in piezoelectric materials; the bulk waves, Rayleigh waves, Love waves and Bleustein-Gulyaev waves are considered. The fourt section with ten references deals with the analytical and experimental studies concerning the strength and failure of piezoelectric materials; these studies are of recent origin, and in fact, they began with the discovery and manufacturing of piezoceramics. The fifth section with eighteen references emphasizes the methods of numerical solutions for the equations of piezoelectric elements. Certain remarks and indications on future possible trends in piezoelectricity conclude the review article.

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[1] Dökmeci, M.C., "Theory of Vibrations of Coated, Thermopiezoelectric Laminae", J. Math. Phys., 19 (1), pp.109-126 (1978).

[2] Dökmeci, M.C., "Recent Advances: Vibrations of Piezoelectric Crystals", Int. J. Engng. Sci., 18 (3), pp.431-448 (1980).

[3] Dökmeci, M.C., "Dynamic Applications of Piezoelectric Crystals; Part I: Fundamentals, Part II: Theoretical Studies, and Part III: Experimental Studies", The Shock and Vibration Digest, 15 (3), pp.9-20, 15 (4), pp.15-26, and 15 (5), pp.11-22 (1983).

B. (2) In the remainder of the contract period, to reproduce some or all the fundamental equations of piezoelectricity with initial stresses, a variational principle is formulated: Then, by using the variational principle together with the series expansions of mechanical displacements and electric potential, the lower-order equations of piezoelectric structural elements are obtained. Further, applications to certain special cases are taken up.

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DAJA45-86-C-0005

(5) 2nd Periodic Report

March 1986-July 1986

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B. (1) The second part of study, following the first,[1] deals with the derivation of the lower order equations of piezoelectric elements under initial stresses. To formulate the lower order equations, first Mindlin's[2] method of reduction is described for a piezoelectric continuum with initial stresses, that is, the appropriate variational principles are derived and the series expansions of field variables are introduced. Next, by use of this method of reduction, one-and two-dimensional equations of piezoelectric strained elements are deduced from the three-dimensional equations of piezoelectricity.

To reproduce some or all the fundamental equations of piezoelectricity with initial stresses, the pertinent variational principles are formulated which allow us to consistently establish the approximate, lower order equations of piezoelectricity as well as to readily provide a direct method of approximate solution. Starting with Hamilton's principle,[3] a variational principle is first derived for a piezoelectric continuum with initial stresses. This variational principle leads to the stress equations of motion, the charge equations of electrostatics and the associated boundary conditions of tractions and surface charge, as its Euler equations. The rest of the fundamental equations of piezoelectric strained continuum remains as the constraints conditions for the variational principle. The constraint conditions are often burdensome and hence undesirable in certain cases of direct approximate solutions. Thus, they are removed by use of Friedrichs's transformation,[4] that is, the dislocation potentials and Lagrange undetermined parameters, and certain quasi- or differential-type of variational principles are obtained.[5,6] Further, in place of Hamilton's principle, by using the principle of virtual work and again applying Friedrichs's transformation, similar quasi-variational principles are formulated for the piezoelectric continuum as well as for other types of continuum.[6-8]

Next, a power series expansions for the mechanical displacements and electric potential of a quartz bar of uniform cross-section is inserted into the quasi-variational principle of piezoelectric continuum which is then integrated over a cross-section of the quartz bar. Thus, a system of nonlinear electroelastic equations of wave propagation and vibrations is consistently obtained for the initially slender quartz bar which is referred to a set of right-handed Cartesian convected (intrinsic) coordinates.[5] The system of governing equations consists of the one-dimensional, electric potential and displacement expansions, linear electric field and nonlinear strain distributions, nonlinear stress equations of motion, linear charge equation of electrostatics, natural boundary conditions of tractions and surface charge, boundary conditions of electric potential and mechanical displacements, nonlinear constitutive equations and initial conditions of displacements and electric potential. These electroelastic governing equations of higher orders of approximation in which account is taken of only the elastic nonlinearities accommodate all the types of extensional, flexural and torsional motions of thin quartz bar. Also, special motions of quartz bar and in particular, those of quartz bar with initial stresses are indicated. Lastly, the fully linearized governing equations of quartz bar are considered, the uniqueness is examined in their solutions, and the sufficient conditions are enumerated for the uniqueness.[9-10] Further, it is worthwhile to note that the the vibrations of piezoelectric discs under initial stresses have been treated by the author[11] as well.

[1*] Dökmeci, M.C., "Dynamic Applications of Piezoelectric Crystals", submitted for publication in The Shock and Vibration Digest.

[2] Mindlin, R.D., Lecture Notes on the Theory of Beams and Plates, Columbia

University, New York (1968); and see also, R.D. Mindlin and Applied Mechanics, Pergamon Press, London (1974).

[3] Tiersten, H.F., Linear Piezoelectric Plate Vibrations, Plenum Press, New York (1969).

[4] Tiersten, H.F., "Natural Boundary and Initial Conditions from a Modification of Hamilton's Principle", J. Math. Phys., 9, pp.1445-1451 (1968).

[5*] Dökmeci, M.C., "Nonlinear Electroelastic Equations of Wave Propagation and Vibrations in Quartz Bars", 40th Annual Frequency Control Symposium, Philadelphia, PA., May 1986.

[6*] Dökmeci, M.C. and N. Sarıgül, "Certain Integral and Differential Types of Variational Principles of Mathematical Physics", International Congress of Mathematicians, Berkeley, CA., August 1986.

[7*] Dökmeci, M.C. and N. Sarıgül, "The Principle of Virtual Power Applied to Polar Incompressible Anisotropic Fluids and Associated Quasi-variational Principles", Tenth U.S. National Congress of Applied Mechanics, Univ. Texas at Austin, TX., June 1986.

[8*] Dökmeci, M.C., "The Principle of Virtual Work Applied to Nonlinear Piezoelectric Continuum and Some Associated Variational Principles", Ann. Meet. Soc. Engng. Science, State Univ. New York at Buffalo, August 1986.

[9] Knops, R.J. and L.E. Payne, Uniqueness Theorems in Linear Elasticity , Springer-Verlag, New York (1971).

[10] Dökmeci, M.C., "An Isothermal Theory of Anisotropic Rods", J. Engng. Math., 9, pp.311-322 (1975).

[11*] Dökmeci, M.C., "Vibrations of Piezoelectric Discs under Initial Stresses", Proc. 39th Annual Symposium on Frequency Control, pp.431-435, IEEE, New York (1985).

(*)acknowledges the research sponsored in part by the United Sates Army through

its European Research Office.

B. (2) In the remainder of the contract period, by using the generalized quasi-variational principles of piezoelectric continuum, the system of two-dimensional approximate equations of a piezoelectric strained laminae will be deduced from the three-dimensional equations of piezoelectricity. Similarly, a hollow, cylindrical piezoelectric composite shell coated with conducting electrodes will be studied. Further, the papers[6,8] will be prepared for presentation at the technical meetings in August 1986, and in particular, the final (annual) technical report will be written down.

B. (3) The author has attended the 40th Annual Frequency Control Symposium, Philadelphia, PA., May 1986, presented the paper[5*] and met the interested people.

5125 PH.

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(5) 3rd Periodic Report

August 1986-March 1987

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B. (1) The third part of study, following the second,[1] is carried out for the primary aim of a systematic derivation of the electroelastic equations of piezoelectric one-and two-dimensional elements subjected to a state of initial stresses. To deduce the lower order equations of strained piezoelements from the three-dimensional equations of electroelasticity, Mindlin's[2,3] method of reduction is described and a unified variational principle[4] is derived for the three-dimensional equations. Then, by use of the unified variational principle together with the series expansions of field variables, the governing equations are derived for the coupled nonlinear vibrations of quartz rectangular bars,[5] those for the dynamics of piezoelectric rods under initial stresses,[6] those for the dynamics of piezoceramic shells under initial stresses[7] and those for the thermopiezoelectric effects in the high frequency vibrations of rods[8], and also the derivation of a nonlinear mathematical model is presented for the dynamics of crystal plates[9].

Toward establishing the electroelastic equations of incremental motions of piezoelements, first the fundamental differential equations of strained piezoelectric medium are expressed as the Euler-Lagrange equations of a unified variational principle. The variational principle has particular advantageous for establishing the electroelastic equations of elements. To derive the unified principle, the principle of virtual work is applied to the piezoelectric continuum by computing the variations of the internal, electric and kinetic energies and the virtual work done by the prescribed surface charge and tractions. Then, by carrying out the indicated variations, a two-field variational principle is obtained which yields only the stress equations of incremental motions, the charge equation of electrostatics and the associated natural boundary conditions of surface charge and tractions. The rest of the fundamental equations remains as the constraints of the variational principle,

which are most often undesirable by computational economy. To remove the constraints, Friedrichs's transformation is applied, and hence the unified variational principle is derived. This principle generates the divergence equations, the gradient equations, the constitutive relations and the natural boundary conditions for the piezoelectric medium under initial stresses, as its Euler-Lagrange equations, and it recovers the principle[4,10] where Hamilton's principle is taken as a point of departure.

The unified variational principle is followed by the electroelastic equations for the dynamics of piezoceramic shells under initial stress. To begin with, attention is confined to a description of the geometry of piezoceramic shell which occupies a finite, regular and bounded region of space, with no singularities of any type. Under the usual assumptions of regularity and smoothness of elastic shells, the incremental components of mechanical displacements and the electric potential are represented by the expansions in the series of Legendre polynomials in the thickness coordinate. The series expansions with sufficient kinematic freedom to account for all the significant mechanical and electrical effects are used so as to obtain the distributions of strain and electric field. In consistent with the expansions, the resultants of mechanical and electrical field quantities are defined across the thickness, and then the macroscopic constitutive relations are found for the piezoceramic shell with its thickness polarization. To derive the remainder of the electroelastic equations of piezoceramic shell, the series expansions are inserted into the unified variational principle, the suitable integrations are performed across the thickness by utilizing the resultants of field quantities, and hence the two-dimensional macroscopic, stress equations of incremental motion and charge equations of electrostatics, the natural boundary conditions and the initial conditions are obtained, in a systematic manner, for the

piezoceramic shell. Then, the electroelastic equations of successively higher orders of approximation of piezoceramic shell are truncted properly as deemed desirable, in any specific case. These equations accommodate all the extensional, flexural and torsional types of incremental motions of piezoceramic shell coated with conducting electrodes. Further, special motions and geometry of piezoceramic shell are pointed out, and in particular, the case of piezoceramic cylindrical shell is considered. By replacing the shifter between the space and surface tensors by Kronecker's delta, that is, by abrogating the curvature effects, the electroelastic equations of strained piezoceramic plate of any geometric shape are found. Lastly, the resulting equations are shown to agree with and contain those of piezoceramic shell with no initial stress and those of elastic shell as well.[cf. 11]

[1*] Dökmeci, M.C., "Nonlinear Electroelastic Equations of Wave Propagation and Vibrations in Quartz Bars", Proc. 40th Ann. Frequency Control Symposium, pp.168-178, IEEE, New York (1986).

[2] Mindlin, R.D., Lecture Notes on the Theory of Beams and Plates, Columbia University, New York (1968); see also, R.D. Mindlin and Applied Mechanics, Pergamon Press, London (1974).

[3] Tiersten, H.F., Linear Piezoelectric Plate Vibrations, Plenum Press, New York (1969).

[4*] Dökmeci, M.C., "Certain Integral and Differential Types of Variational Principles in Nonlinear Piezoelectricity", pp.1-40, submitted for publication.

[5*] Dökmeci, M.C., "Coupled Nonlinear Vibrations of Quartz Rectangular Bars", paper at Ist European Frequency and Time Forum, Besancon, France, March 1987

[6*] Dökmeci, M.C., and E.E. nanl'D., "Dynamics of Piezoelectric Rods under Initial

Stresses", paper at the 113th Meet. Acoust. Soc. Am., Indianapolis, Indiana, May 1987.

7*Dökmeci, M.C., "Dynamics of Piezoceramic Shells under Initial Stress", paper at the 41st Ann. Symposium on Frequency Control, Philadelphia, Pennsylvania, May 1987.

8*Dökmeci, M.C., "Thermopiezoelectric Effects in the High Frequency Vibrations of Rods", submitted for presentation IEEE Ultrasonics Symp., October 1987.

9*Dökmeci, M.C., "Derivation of a Nonlinear Mathematical Model for Dynamics of Crystal Plates", paper at Sixth International Conference on Mathematical Modelling, St. Louis, Missouri, August 1987.

10*Dökmeci, M.C. and N. Sarıgül, "Certain Integral and Differential Types of Variational Principles of Mathematical Physics", Abstr. International Congress of Mathematicians, pp.269, Univ. California, Berkeley, August 1986.

11*Dökmeci, M.C., "Theory of Vibrations of Coated, Thermopiezoelectric Laminae", J. Math. Phys., 19, pp.109-126 (1978).

(*)acknowledges the research sponsored in part by The United States Army through its European Research Office.

B. (2) In the extended period of contract, the purpose of research project is (i) to study the effect of material nonlinearity and (ii) to examine the effect of temperature, following the methodology of the second and third interim reports. In addition to these, (iii) the project will involve numerical solutions of specific problems by using the general results obtained in the second and third part of study. Moreover, the papers[*,8,9,+] will be prepared for presentation at the technical meetings and, in particular, the final technical report will be written down.

[+]*Dökmeci, M.C., nanI'D., E.E., and Sarıgül, N., "On Some Variational Principles in Contact Elasticity", 20th Midwestern Mechanics Conference, Purdue University, West Lafayette, IN., September 1987.

B. (3) The author has attended and presented the papers* of Ref.10, Ref.[‡] and Ref.7, respectively, at

(i) The International Congress of Mathematicians, Univ. Calif., Berkeley, CA., August 1986,

(ii) The 23rd Annual Meeting of the Society of Engineering Science, State Univ. New York at Buffalo, N.Y., August 1986, and

(iii) The 41st Annual Frequency Control Symposium, Philadelphia, PA., May 1987,

and also he has met the interested people and discussed certain problems of interest.

[‡]*Dökmeci, M.C., "The Principle of Virtual Work Applied to Nonlinear Piezoelectric Continuum and Associated Variational Principles".

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